1991

INTERNATIONAL CONFERENCE ON THE ROLE OF THE POLAR REGIONS IN GLOBAL CHANGE: PROCEEDINGS OF A CONFERENCE HELD JUNE 11-15, 1990 AT THE UNIVERSITY OF ALASKA FAIRBANKS

PP. 372-377 IN G. WELLER, C. L. WILSON, B. A. B. SEVERIN (EDS.) GEOPHYSICAL INSTITUTE, UNIV. OF ALASKA, FAIRBANKS

Methane Emissions from Alaska Arctic Tundra in Response to Climatic Change

NASA-TM-111750

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ABSTRACT

In situ observations of methane emissions from the Alaska North Slope in 1987 and 1989 provide insight into the environmental interactions regulating methane emissions and into the local- and regional-scale response of the arctic tundra to interannual environmental variability. Inferences regarding climate change are based on *in situ* measurements of methane emissions, regional landscape characterizations derived from Landsat Multispectral Scanner satellite data, and projected regional-scale emissions based on observed interannual temperature differences and simulated changes in the spatial distribution of methane emissions.

Our results suggest that biogenic methane emissions from arctic tundra will be significantly perturbed by climatic change, leading to warmer summer soil temperatures and to vertical displacement of the regional water table. The effect of increased soil temperatures on methane emissions resulting from anaerobic decomposition in northern wetlands will be to both increase total emissions and to increase interannual and seasonal variability. The magnitude of these effects will be determined by those factors affecting the areal distribution of methane emission rates through regulation of the regional water table. At local scales, the observed 4.7°C increase in mid-summer soil temperatures between 1987 and 1989 resulted in a 3.2-fold increase in the rate of methane emissions from anaerobic soils. The observed linear temperature response was then projected to the regional scale of the Alaska North Slope under three environmental scenarios. Under moderately drier environmental conditions than observed in 1987, a 4°C mid-summer increase in soil temperatures more than doubled regional methane emissions relative to the 1987 regional mean of 0.72 mg m^{-2} hr^{-1} over the 88,408 km^2 study area. Wetter environmental conditions led to a 4- to 5-fold increase in mid-summer emissions. These results demonstrate the importance of the interaction between the relative areal proportion of methane source areas and the magnitude of summer substrate temperatures in determining whether emissions from decomposition processes in northern ecosystems represent a significant global source and a potential positive feedback to climatic change.

INTRODUCTION

The northern high latitudes face a potentially unprecedented rate of climatic warming as a direct consequence of global increases over the past century in the atmospheric concentrations of infrared-absorbing gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [Bolin et al., 1986; Dickinson and Cicerone, 1986; Ramanathan et al., 1987]. As a direct result of the past and anticipated continued atmospheric inputs of these "greenhouse gases," current global circulation models project that mean annual temperatures for the Arctic may increase between 3–8°C within the next century [Hansen et al., 1988; Post, 1990]. This climatic change is expected to result in earlier spring thaws, longer growing seasons, and 2–4°C elevated summer temperatures. Precipitation patterns may also change, although current projections are still highly uncertain. If these organic-rich and temperature-limited ecosystems [Chapin, 1984] respond to climatic change by releasing substantially greater quantities of CO_2 and CH_4, the climatic warming trend may be enhanced [Lashof, 1989] and the global carbon cycle significantly affected [Miller, 1981; Billings, 1987].

Empirical and atmospheric modeling studies indicate that the northern high latitude wetlands may represent one of the largest natural sources of CH_4 globally as a result of seasonal anaerobic microbial decomposition of organic materials in the active thaw layer. More than half of the wetlands area of the earth lies in the boreal region north of 50°N latitude [Matthews and Fung, 1987; Aselmann and Crutzen, 1989] and over 20% of the earth's total organics may be stored in these ecosystems as frozen or recalcitrant materials in the soils and peats [Post et al., 1985; Gorham, 1988]. Seasonal CH_4 emissions from these ecosystems are estimated to currently account for 6–10% of all CH_4 sources and 16–63% of all natural wetland sources [Aselmann and Crutzen, 1989]. If subjected to climatic warming, these ecosystems may respond by releasing substantially greater quantities of carbon to the atmosphere as a consequence of increased rates of decomposition operating over longer seasons of biological activity and on increasing quantities of organic materials as the permafrost thaws. Examination of arctic methane emissions under variable interannual meteorological conditions may provide insight into the response of northern ecosystems to anticipated climatic change.

In this paper we address observed and projected CH_4 emissions from arctic tundra in relation to anticipated climatically induced changes in soil temperature and water table position. Our conclusions are based upon measured *in situ* CH_4 emissions during the summers of 1987 and 1989 from the North Slope of Alaska, regional land cover characterizations derived from satellite observations, and estimated regional-scale emissions derived from observed interannual temperature differences and simulated changes in water table position.

METHODS

The region of study is an 88,408 km² area representative of the Arctic Coastal Plain and Foothill provinces of the Alaska North Slope (Figure 1). Estimates of mid-summer regional CH_4 emission rates for select climatic scenarios were derived through integration of satellite-based land cover characterizations and *in situ* observations of CH_4 emissions from early August of 1987 and 1989.

At the regional scale, digital classifications of Landsat Multispectral Scanner (MSS) data [Morrissey and Ennis, 1981; Walker et al., 1982] defined the land cover categories and their relative areal proportions subsequently used to calculate regional emission estimates. The spectrally based classification corresponded to vegetation type and density as well as to the presence or absence of surface water. These land cover classes nominally represented "Dry Tundra," "Moist Tundra," "Wet Tundra," "Very Wet Tundra," and "Water" at 50 m² spatial resolution.

In situ sample allocations differed between 1987 and 1989. In 1987 the allocation was defined to regionally represent both the Arctic Coastal Plain and Arctic Foothills physiographic provinces of the North Slope. More specifically, each land cover class was sampled in proportion to its relative areal representation and to anticipated variances in emissions at the regional scale. Within each site sampled, a secondary allocation represented the microtopography and location of the local water table relative to the surface on a spatial scale of approximately 0.5 m². Ten microtopographic features were identified for sampling, e.g., "low center polygonal basins," "rims," "troughs," "sedge meadows," "high centered polygonal basins," "frost boils," "sedge tussocks," "inter-tussock areas," "lake-over emergent vegetation," and "lake-open water." The location of the water table was categorized as "below" ($z \leq -5$ cm), "at" ($-5 > z \leq 0$ cm), or "above" ($z > 0$ cm) the surface. In total, the area of study was represented by 122 emissions observations representing 57 spatially independent sites. Additional details of the sample allocation are given in Morrissey and Livingston [1991].

The regional mean rate of CH_4 emissions (F) was estimated on the basis of a two-tiered stratified approach [Cochran, 1953] using the relative areal proportions of the local and regional categorizations as the weighting terms:

$$F = \sum_{i=1}^{m} \sum_{j=1}^{n} (p_{ij} f_{ij}) \tag{1}$$

where p_{ij} represents the relative areal proportion of land cover class i and local-scale microtopographic feature j, and f_{ij} the measured rate of CH_4 emissions.

In 1989, the sample allocation was defined to assess the seasonal variability in emissions at anaerobic (waterlogged) organic sites on the Arctic Coastal Plain. Only data from the two years that were complemental in time (August 1–14) were included in this analysis. To estimate regional-scale emissions for 1989, we initially assumed no net change in the vegetation or hydrological regimes at the regional scale of the North Slope between 1987 and 1989. As such, in this "reference scenario," differences in estimated regional-scale emissions over the 3-year period reflect only observed interannual differences in the rates of emissions at the local scale. The 1989 CH_4 emission rates for each land cover class were thus calculated as:

$$\mathcal{E}_{1989} = \left(\frac{\epsilon_{1989}}{\epsilon_{1987}}\right) (\mathcal{E}_{1987}) \tag{2}$$

where $\mathcal{E}$ represents the ecosystem CH_4 emissions rate and ϵ the *in situ* emission rate from anaerobic organic soils.

The sensitivity of regional CH_4 emissions to interaction between the observed interannual differences in the emission rates and changes in the areal representation of the methane source areas was explored in a simulation exercise and subsequently interpreted in light of the potential impacts of climatic change. Two scenarios were examined in addition to the reference scenario described above. "Dry" and "Wet" environmental conditions were simulated by assuming arbitrary shifts in the relative areal proportions of the regional land cover classes. The "Dry" climate scenario was simulated by a 1/3 proportional loss in inundated surface area over the North Slope, represented as a shift from "Very Wet Tundra" to "Wet Tundra," "Wet Tundra" to "Moist Tundra," and "Moist Tundra" to "Dry Tundra." In the "Wet" climate scenario, an increase in surface inundation was simulated by a 1/3 areal proportional shift from "Wet Tundra" to "Very Wet Tundra" only. The areal extent of well-drained soils ("Moist Tundra") was assumed to be unaffected by a moderate elevation of local water tables. Similarly, the areal proportion of impounded lakes ("Water") was assumed unchanged in both the "Dry" and "Wet" scenarios.

Hydrology plays a major role in defining arctic ecosystem structure and function, thus providing the basis for the scenarios examined. Over large areas of arctic tundra, topography is known to vary on a scale of centimeters to meters. In such areas, even moderate vertical displacement of the local water table on seasonal to decadal time scales can result in substantial shifts in the areal extent of inundated (anaerobic) and drained (aerobic) substrates. The significance of this lies in the well-documented correspondence between the position of the local water table relative to the surface and microtopographic relief, substrate temperature profiles, nutrient and organic contents, ecosystem composition and productivity, and the mode (aerobic vs. anaerobic) of organic degradation [Bunnell et al., 1980; Webber et al., 1980; Walker, 1985]. Moreover, the position of the local water table in these ecosystems has been directly related to the processes of CO_2 and CH_4 production, uptake, and release to the atmosphere [Peterson et al., 1984; Svensson and Rosswall, 1984; Sebacher et al., 1986; Crill et al., 1988; Conrad, 1989; Moore and Knowles, 1989; Morrissey and Livingston, 1991].

Emissions Measurements

In situ measurements of CH_4 emissions were made using enclosed chambers deployed over a 15- to 30-minute period within which the atmospheric concentration of CH_4 was monitored over time. Samples were collected in 10-ml glass syringes and analyzed within 12 hours using isothermal gas chromatography and a flame ionization detector. Net rate of emissions was calculated as the average rate of change in CH_4 concentration within the chambers normalized for the molar volume of the chambers at the ambient near-surface temperature. The minimal detectable rate of emissions averaged less than 0.14 mg CH_4 m^{-2} hr^{-1}. Details of the sampling protocol and analysis are given in Morrissey and Livingston [1991].

RESULTS

Observed Interannual Differences

Summer temperature regimes for the North Slope differed significantly between 1987 and 1989. Whereas mean monthly air temperatures at Prudhoe Bay for July and August of 1987 differed little from the 30-year mean, 1989 temperatures represented record highs [NOAA, 1987, 1989]. Mid-summer (July and August) mean daily air temperatures averaged 7.7 and 11.8°C in 1987 and 1989 respectively. By mid-August, cumulative daily temperatures above 0°C for the two years differed by nearly 600 degree-days (713 compared to 1302°C-da in 1989). Soil temperatures in anaerobic soils also differed significantly at 10 cm depths, averaging

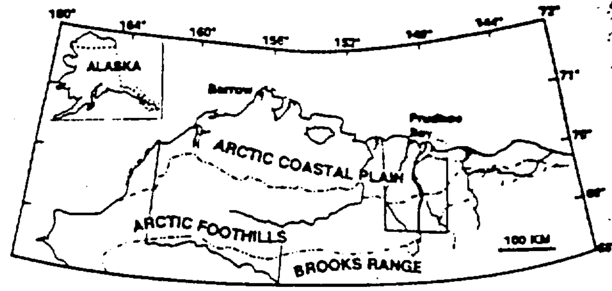

Figure 1. The Alaska North Slope. Regional estimates of emissions were calculated for that area (88,408 km²) represented by Landsat MSS digital data (shaded).

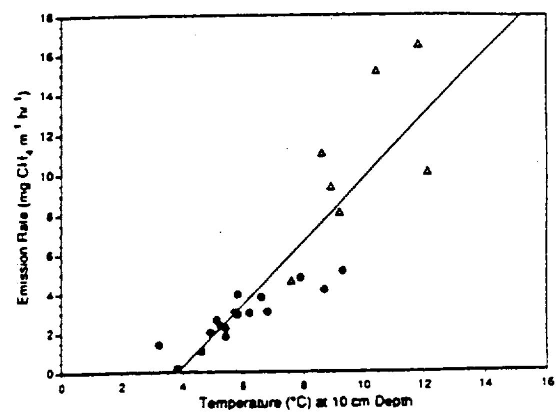

Figure 2. Mid-summer rates of methane emissions from anaerobic organic soils as a function of substrate temperatures at 10 cm depth. Filled symbols represent spatially independent observations over August 1–13, 1987; open symbols represent the average between spatially paired observations between August 2–4 and August 9–11, 1989.

4.7 and 9.4°C in 1987 and 1989. Mid-summer thaw depths ranged mostly between 35 and 45 cm with no clear relation to coincident soil temperatures at 10 cm depths and no measurable difference between years ($p > 0.2$; t-test).

Mid-summer rates of CH_4 emissions from anaerobic (waterlogged) organic soils on the North Slope were linearly related to ambient substrate temperatures at 10 cm depths both within and between years (Figure 2). As a consequence, local-scale rates of emissions differed dramatically between the summers of 1987 and 1989. Over the total observed temperature range of 3.1 to 14.9°C, CH_4 emissions (E) from anaerobic organic soils ranged between 1.6 and 23.6 mg m^{-2} hr^{-1} corresponding to a temperature (T°C) response from spatially independent sites of: $E = 1.590T - 6.094$, $r^2 = 0.77$, $n = 24$. Local-scale methane emissions from anaerobic sites in early August of 1989 were over four times greater than in 1987, averaging 11.7 mg m^{-2} hr^{-1}, 1.4 std. err., $n = 9$ and 2.8 mg m^{-2} hr^{-1}, 0.3 std. err., $n = 17$ respectively. Within 1989, emission rates for repeatedly observed sites also demonstrated a temperature response between the first and second weeks of August ($p=0.0001$, paired t-test, $n=9$), averaging 9.1 and 14.4 mg m^{-2} hr^{-1} on 7.7 and 11.1°C soils. As expected, the relation between depth of thaw and emission rates was poorly defined ($r^2 = 0.24$, $p = 0.03$).

CLASS	Reference Climate	"Dry" Climate	"Wet" Climate
DRY TUNDRA	0	0.204	0
MOIST TUNDRA	0.618	0.479	0.618
WET TUNDRA	0.196	0.161	0.131
VERY WET TUNDRA	0.089	0.060	0.154
WATER	0.098	0.098	0.098

Table 1. Areal proportions of Landsat MSS land cover classes used in the calculation of Alaska North Slope regional CH_4 emissions under observed and simulated climatic regimes.

CLASS	1987	1989 Lower Estimate	1989 Upper Estimate
DRY TUNDRA	0	0	0
MOIST TUNDRA	0.39	0.39	1.59
WET TUNDRA	1.02	4.17	4.17
VERY WET TUNDRA	2.59	10.58	10.58
WATER	0.47	0.47	1.92
NORTH SLOPE TOTAL	0.72	2.05	2.93

Table 2. Mid-summer methane emission rates for Landsat MSS land cover classes used in the calculation of North Slope regional emissions under the reference scenario. Units of emission are in mg CH_4 m^{-2} hr^{-1}. Total area represented is 88,408 km^2.

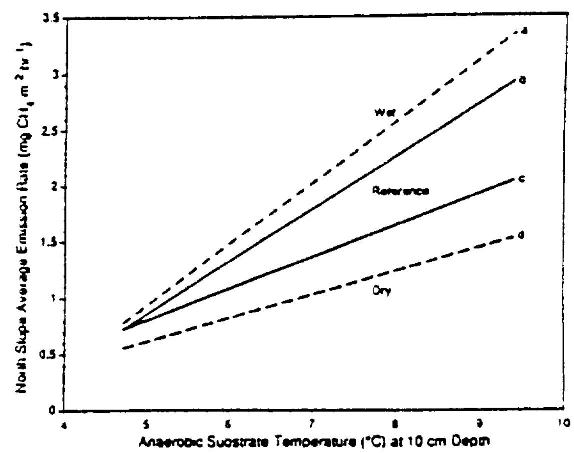

Figure 3. Mean mid-summer regional-scale methane emission rates projected for the Alaska North Slope. Solid lines (b and c) represent upper and lower projected emissions based upon observed 1987 and 1989 ecosystem parameters (reference scenario). Dashed lines represent projected emission rates under simulated "Wet" (a) and "Dry" (d) climatic regimes.

Projected Regional-Scale Emissions

Simulation parameters and results of the 1987 and 1989 regional emissions estimates and climatic change simulations are summarized in Tables 1 and 2, and Figure 3. Local-scale mid-summer emission rates were based upon actual 1987 and 1989 observations. Regional (88,408 km^2)-scale projections are based upon three water table scenarios derived from the Landsat MSS regional characterization. Regional-scale 1987 mid-summer CH_4 emissions from the North Slope totaled 63,654 kg hr^{-1}, averaging 0.72 mg CH_4 m^{-2} hr^{-1}. Under the assumption of no change in the regional water table (the reference scenario), mid-summer 1989 regionally averaged emissions were estimated between 2.05 and 2.93 mg CH_4 m^{-2} hr^{-1} (Figure 3, lines b and c). This represents the potential for a more than doubling in CH_4 emission rates at the regional scale for only a 2°C increase in mid-summer substrate temperatures at 10 cm depth. Both poorly and well-drained land cover classes are expected to contribute to the increased regional emissions at the higher substrate temperatures, although their relative contributions are temperature dependent. Given substrate temperatures comparable to those observed in 1989, "Moist Tundra," "Wet Tundra," and "Very Wet Tundra" are expected to contribute approximately equally (34, 28, and 32% respectively) to the regional emissions total despite a more than 2-fold difference in their relative areal proportions (Table 1).

Because of its vast areal extent both on the Alaska North Slope (Table 1) and globally, "Moist Tundra" will play a significant role in the arctic response to climatic change. The interaction between areal extent and emission rates for "Moist Tundra" is demonstrated in the range of the projected regional emissions estimates in the reference scenario (Figure 3, lines b and c). The difference in the regional estimates is due almost entirely to uncertainty in the emissions response of "Moist Tundra" to increased temperatures (Table 2). The lower estimate for the 1989 reference scenario assumes that carbon limitations and microbial CH_4 consumption from the shallow organic and aerobic soils characterizing "Moist Tundra" will result in no net increase in CH_4 emission rates even under warmer environments. No increased emission rates from "Water" is also assumed. The upper estimate for the reference scenario assumes that the CH_4 emissions-temperature response of "Moist Tundra" will be proportionally similar to the more anaerobic and organic-rich classes characteristic of the Coastal Plain. Emissions from "Water" also may be expected to increase under warmer environments, perhaps in response to increased ebullition transport of CH_4 to the surface. However, in a regional context, "Water" represents less than 10% of the total area, and combined with its low emission rate, is expected to contribute only about 6% of the regional CH_4 emissions total even under warm environments.

The interaction between substrate temperatures and the relative areal proportion of inundation is critical in determining both regional and annual CH_4 emissions. As both factors vary on seasonal and interannual scales, so will regional CH_4 emissions. For example, if midsummer substrate temperatures differ little from those observed in 1987, regional CH_4 emission rates are not expected to vary greatly even with moderate changes in the areal distribution of the contributing land cover classes. Projected regional CH_4 emission rates for "Dry" and "Wet" scenarios at 4.7°C (1987) substrate temperatures are between 0.55 and 0.82 mg m^{-2} hr^{-1} (Figure 3, lines a and d), representing about a 50% range. The difference in regional CH_4 emission rates under

"Dry" and "Wet" environments are projected to increase linearly thereafter with increased substrate temperatures. Subject to a doubling in temperatures at 10 cm depth, as observed between 1987 and 1989, regional CH_4 emissions rates could vary between 1.53 and 3.34 mg m^{-2} hr^{-1} depending on whether the "Dry" or "Wet" scenario is realized. This represents more than a 2-fold increase in emission rates from arctic tundra even under drier environmental conditions than observed in 1987. Moderately wetter conditions could result in a 4.6-fold increase in regional CH_4 emissions rates.

DISCUSSION

Methane emissions from the northern high latitudes will be significantly perturbed by climatic changes, leading to warmer mid-summer substrate temperatures and to changes in the areal distribution of the CH_4 source areas resulting from vertical displacement of the regional water table. The effect of increased soil temperatures on CH_4 emissions resulting from anaerobic decomposition in northern wetlands will be two fold. If soil temperatures at 10 cm depth are increased 2–4°C above observed 1987 temperatures, CH_4 emission rates are expected to increase several fold. The magnitude of the increase at the regional scale, however, will be determined by the relative areal representation of the sources and sinks. Even under moderately drier environmental conditions, the rate of CH_4 emissions at the regional scale could more than double. The interaction between substrate temperature and areal contributions are expected also to significantly increase the variability in CH_4 emissions on seasonal and interannual time scales.

Currently, *in situ* observations on the interannual variability of CH_4 emissions from northern ecosystems are limited [Whalen and Reeburgh, 1988], yet the results presented here show that an understanding of the magnitude of this variability may be an integral component in assessing the role of CH_4 emissions in climatic change. The critical factors in estimating regional–annual CH_4 emissions are the regional and seasonal characterization of CH_4 emission rates and the length of the growing season. Projections based upon *in situ* observations from the Alaska North Slope in 1987 and 1989 indicate that interannual differences in mid-summer regional CH_4 emission rates may approach a factor of 3 due to temperature differences alone. Variability in the spatial distribution of CH_4 emissions due, for example, to interannual differences in the amount or timing of summer precipitation is expected to increase this interannual variability in CH_4 emissions even more, perhaps to a factor of 4 to 5 relative to 1987 emissions.

Interannual variability in regional CH_4 emissions related to increased soil temperatures were found to exceed expected variability in emissions due to the length of the growing season. Thirty-year climate records [Tieszen et al., 1980] indicate that thaw season lengths vary by only a factor of 2. Even ignoring seasonal temperature effects, this, at most, contributes a factor of 2 to the interannual variability in CH_4 emissions. Although the global impact of climate-related increases in growing season length is expected to be significant [Lashof, 1989], these results demonstrate that the magnitude of the summer soil temperatures in response to climatic change may be far more significant in determining the rate of CH_4 emissions in northern ecosystems.

Future CH_4 emissions measurement and modeling efforts must account for ecosystem spatial dynamics. Quantitative and dynamic estimation approaches, integrating empirical or process level correspondence between rates of emissions, and environmental parameters with regional-scale characterizations of ecosystem parameters will be required to fully understand the magnitude and variability of CH_4 emissions on regional to global scales. The integration of *in situ* and satellite-based observations demands further attention towards that goal.

ACKNOWLEDGMENTS

The authors are grateful to BP Exploration, Inc. for permitting access to research sites in the Prudhoe Bay region and to the numerous management and staff members who supported this effort. Acknowledgment is also given to Drs. W. Reeburgh and S. Whalen, University of Alaska Fairbanks, for their open discussions on the methane emissions issues and for sharing their facilities. This research was supported by the National Aeronautics and Space Administration Terrestrial Ecosystems and Interdisciplinary Research in Earth Science Programs under RTOPs 677-21-22 and 176-20-34.

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